EE-434 Power Electronics

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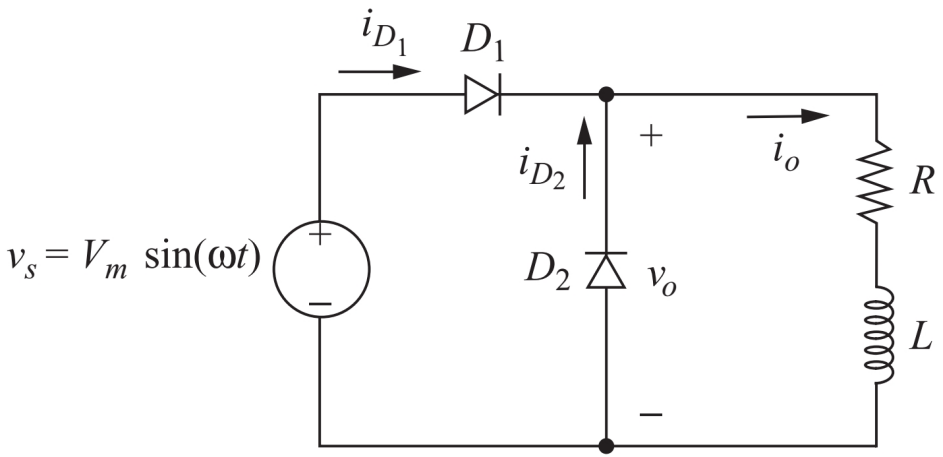
Overview

1. Freewheeling diode
2. Commutation

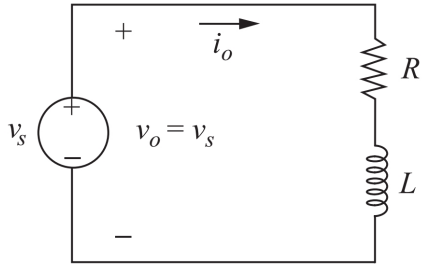
Freewheeling diode

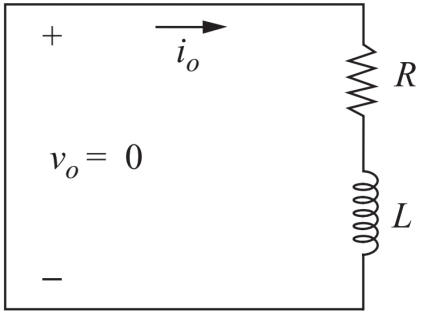
For the inductive load, the presence of negative voltage cause the average output to decrease.
Moreover, the inductive voltage create stress on the power electronic switches.



When D_1 conducts, D_2 is reverse biased. When D_1 is reverse biased, the D_2 conducts.

Freewheeling diode





For $0 \leq \omega t \leq \pi$ D_1 is on and D_2 is off. The circuit is of the form as shown.
The voltage across the load is same as the source.

For $\pi \leq \omega t \leq 2\pi$ D_1 is off and D_1 is on. The circuit is of the form as shown.
The voltage across the RL load is zero

The Fourier series for half-wave rectified sine wave for output voltage is

$$v(t) = \underbrace{\frac{V_m}{\pi}}_{\text{DC part}} + \underbrace{\frac{V_m}{2} sin(\omega_o t)}_{\text{Fundamental}} - \underbrace{\sum_{n=2,4,6\ldots}^{\infty} \frac{2V_m}{(n^2-1)\pi} cos(n\omega_o t)}_{\text{Even harmonics}} \qquad (1)$$

Freewheeling diode

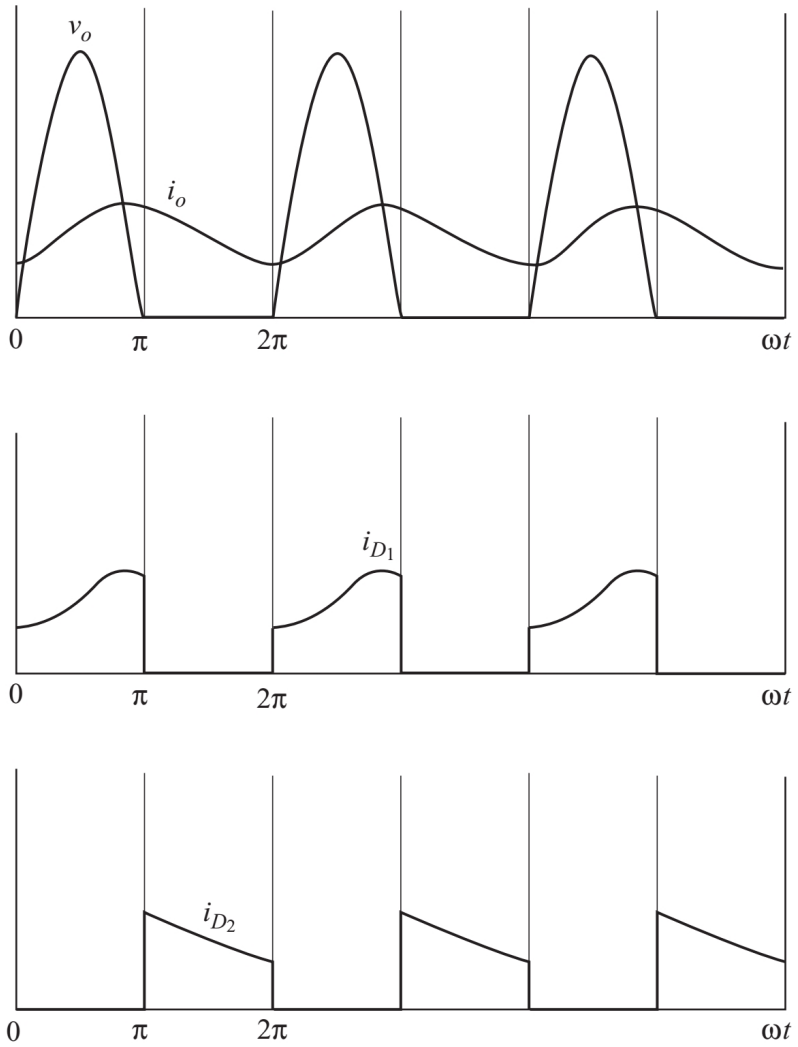


Figure: Key waveforms

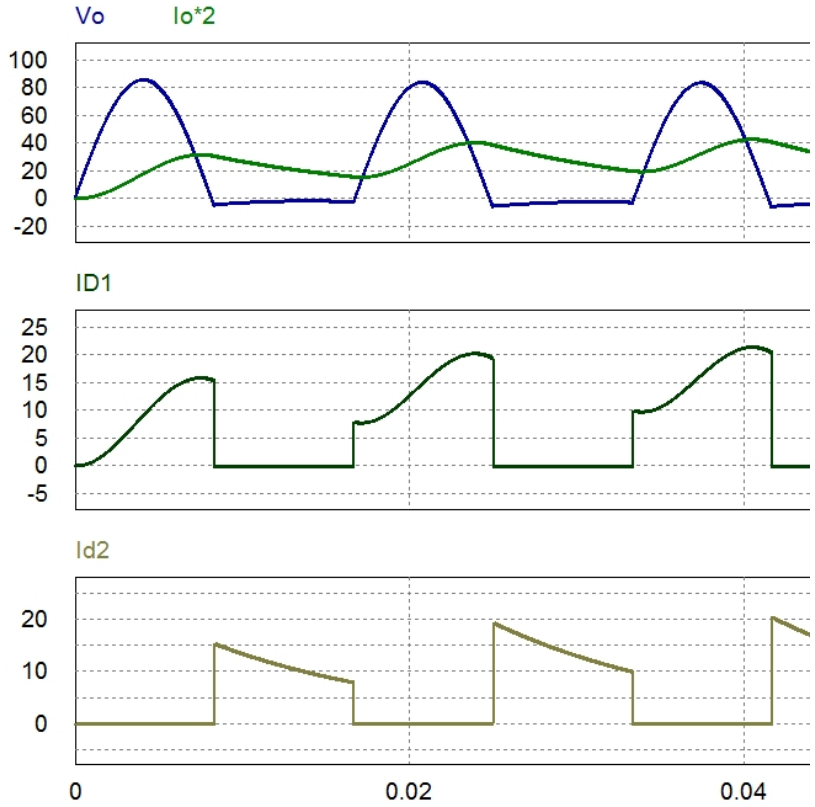


Figure: Simulated waveforms R=2, L=25m, Vp=100 f=60

Example 3-7 — Freewheeling diode

For a half wave free wheeled rectifier, determine the average load voltage and current, the power absorbed by the resistor. Note that R=2Ω and L=25 mH, V_m=100 V, and the frequency is 60 Hz.

Solution

The average voltage is the dc term of (1)

$$V_o = \frac{V_m}{\pi} = 31.8V \qquad (2)$$

The average load current is

$$I_o = \frac{V_o}{R} = 15.9A \qquad (3)$$

Load power is $I_{rms}^2 R$. The rms current is determined from the Fourier components of current. AC current components are determined from phasor analysis

$$I_n = \frac{V_n}{Z_n} \qquad (4)$$

where, $Z_n = |R + jn\omega_o L| = |2 + jn377(0.025)|$.

AC voltage resulting from (1) are

$V_1 = \frac{V_m}{2} = 50V$

$V_2 = \frac{2V_m}{(2^2-1)\pi} = 21.2V$

$V_4 = \frac{2V_m}{(4^2-1)\pi} = 4.24V$

$V_6 = \frac{2V_m}{(6^2-1)\pi} = 1.82V$

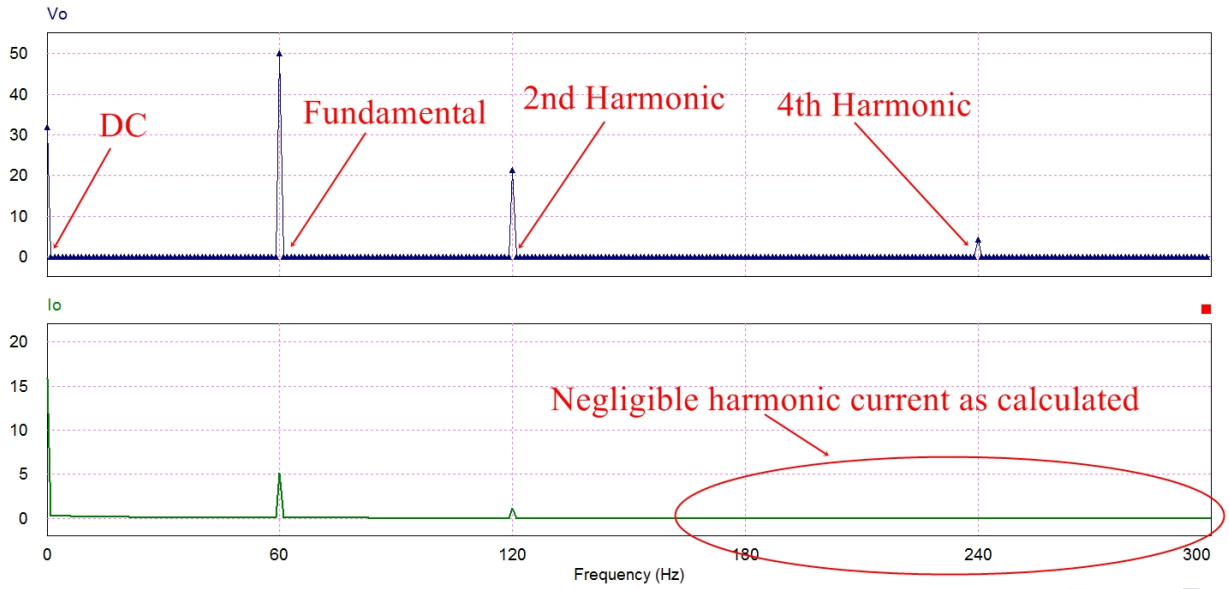
Freewheeling diode

So, the respective current value from fourier terms are $I_0 = \frac{V_0}{Z_0} = 15.9A$
$I_1 = \frac{V_1}{Z_1} = 5.19A$
$I_2 = \frac{V_2}{Z_2} = 1.12A$
$I_4 = \frac{V_4}{Z_4} = 0.11A$
$I_6 = \frac{V_6}{Z_6} = 0.03A$
The rms current is obtained as

$$I_{rms} = \sqrt{\sum_{k=0}^{\infty} I_{k,rms}} \approx \sqrt{15.9^2 + \left(\frac{5.19}{\sqrt{2}}\right)^2 + \left(\frac{1.12}{\sqrt{2}}\right)^2 + \left(\frac{0.11}{\sqrt{2}}\right)^2} = 16.34A \tag{5}$$

Power absorbed by the load is $I_{rms}^2 R = 534W$

Example 3-7 —Simulation



Reducing load current harmonics

The output current is given as

$$I_{output} = I_{dc} + I_{ac} \tag{6}$$

The dc component is desired whereas, ac component constitutes the ripples.The average load current (dc) in the RL load depends only on **RESISTANCE**, owing to the **Ohm's law**.This means that the inductance has no impact on the average (dc) current.However, because of inductive reactance ($X_L = 2\pi fL$), the inductance do have an impact on the ac components. If the inductance is made large enough, the impedance to the ac components will become high, consequently, the output become a pure dc.

$$i_o(t) \approx I_o = \frac{V_o}{R} = \frac{V_m}{\pi R} \qquad \frac{L}{R} \implies \infty \tag{7}$$

A large inductor means ($\tau >> T$) means a constant load current.

$$\Delta I_o \approx 2I_1 \tag{8}$$

Example 3-8 — Freewheeling diode with $\tau = \infty$

For a half wave free wheeled rectifier, determine the average current in each diode, the power absorbed by the resistor and power factor. Note that R=8Ω and L=25H(assumed very large), V_{rms}=240 V, and the frequency is 60 Hz. Later, find L such that the ΔI_{p-p} is 10 percent of the average current.

Solution

(a)The average current is given in (7)

$$i_{\omega t} = I_o = \frac{V_m}{\pi R} = 13.5A \quad (9)$$

This is also the rms current.

The power in resistor is $I_{rms}^2 R$=1459W. The source rms current is

$$I_{s,rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}(13.5)^2 d(\omega t)} = 9.55A \quad (10)$$

Power factor is

$$pf = \frac{P}{V_{s,rms} I_{s,rms}} = 0.637 \quad (11)$$

Each diode conducts for one half cycle. So average current for each diode is $I_o/2$=6.75A

Freewheeling diode

So, the respective current value from fourier terms are $I_0 = \frac{V_0}{Z_0} = 15.9A$
$I_1 = \frac{V_1}{Z_1} = 5.19A$
$I_2 = \frac{V_2}{Z_2} = 1.12A$
$I_4 = \frac{V_4}{Z_4} = 0.11A$
$I_6 = \frac{V_6}{Z_6} = 0.03A$
The rms current is obtained as

$$I_{rms} = \sqrt{\sum_{k=0}^{\infty} I_{k,rms}} \approx \sqrt{15.9^2 + \left(\frac{5.19}{\sqrt{2}}\right)^2 + \left(\frac{1.12}{\sqrt{2}}\right)^2 + \left(\frac{0.11}{\sqrt{2}}\right)^2} = 16.34A \tag{12}$$

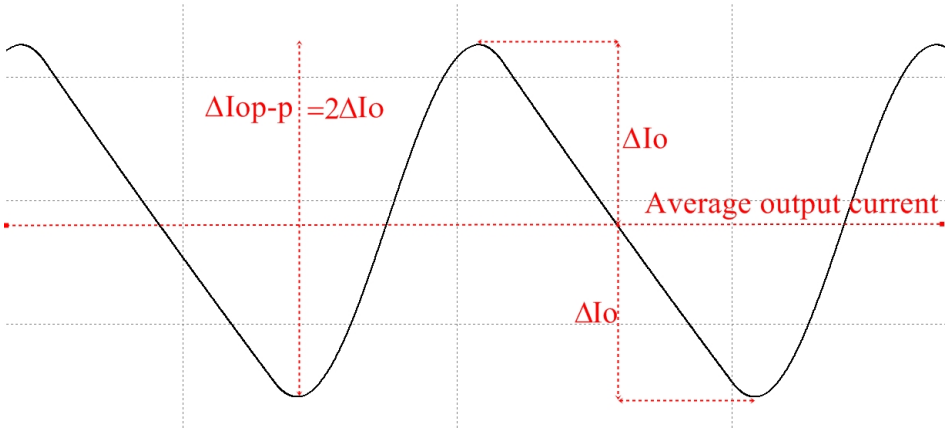
Power absorbed by the load is $I_{rms}^2 R = 534W$

Example 3-8 — Freewheeling diode with $\tau = \infty$

The value of inductance required to ensure the ripple current of 10 percent can be calculated using fourier series.
The voltage input to load of n=1 has amplitude of
$V_m/2 = \sqrt{2}(240)/2 = 170V$.
Also, the peak to peak current must be limited to

$$\Delta I_o = (0.10)(I_o) = (0.10)(13.5) = 1.35A \tag{13}$$

This corresponds to peak ripple of 13.35/2=0.675A



Example 3-8 — Freewheeling diode with $\tau = \infty$

The load impedance at fundamental frequency is

$$Z_1 = \frac{V_1}{I_1} = \frac{170}{0.675} = 251\Omega \tag{14}$$

The load impedance is

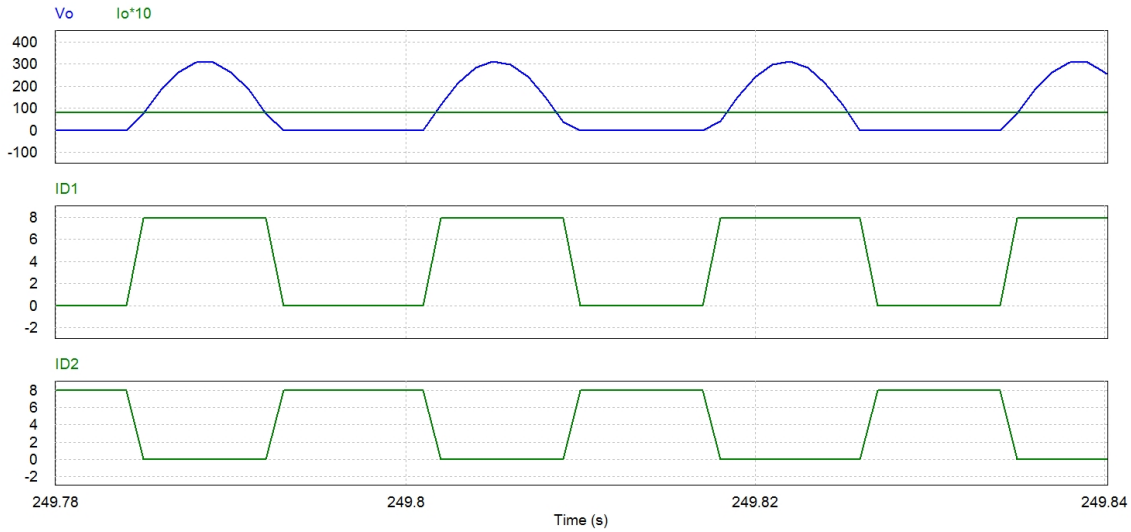
$$Z_1 = 251 = |R + j\omega L| = |8 + j377L| \tag{15}$$

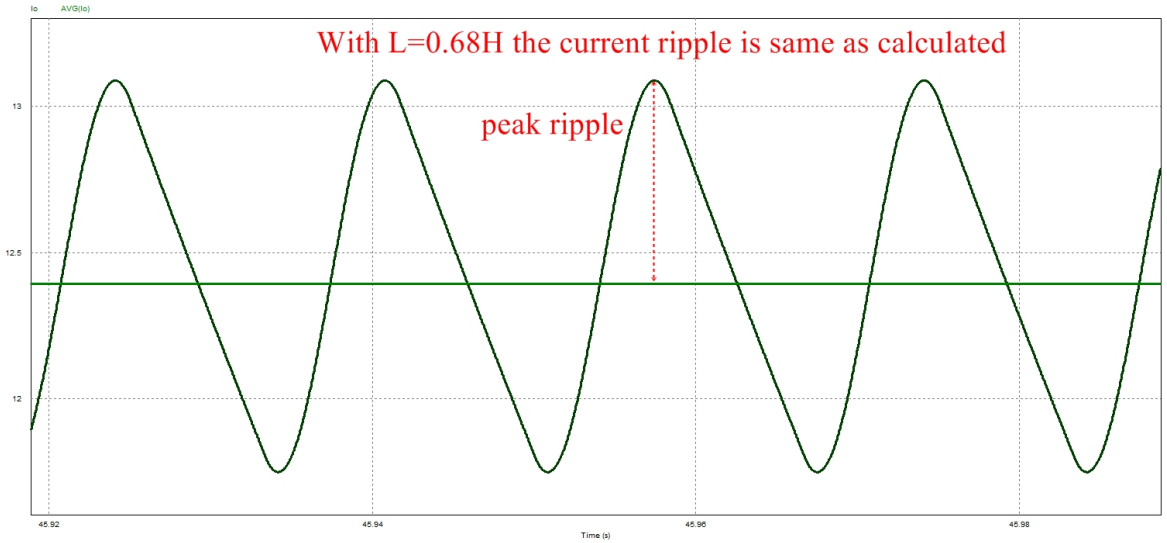
As resistance is very less, therefore,

$$L \approx \frac{Z_1}{\omega} = \frac{251}{377} = 0.67H \tag{16}$$

To compensate the impact of harmonics, L is chosen slightly higher than this value e.g., 0.68H

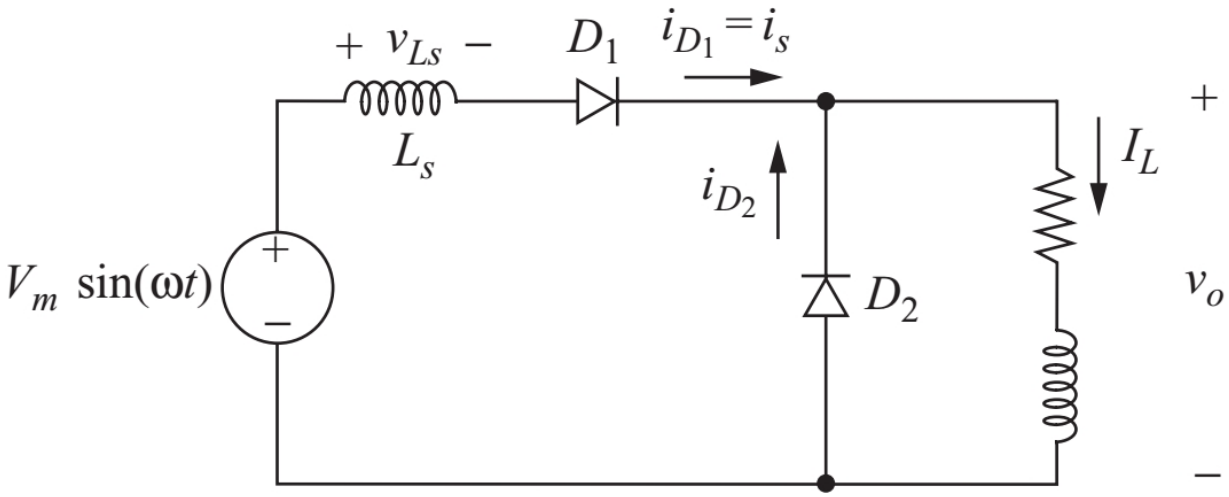
Example 3-8 —Simulation





Effect of source inductance

A more practical realization of source is to add inductive reactance in series.



For the above circuit it is assumed that the load inductance is large enough such that the load current is constant.
It is also assumed that at t=0, the positive half cycle shall appear as input.

Effect of source inductance

At $t = 0^-$, the load current is I_L, D_1 is off and D_2 is on.
At t=0, the source voltage becomes positive and D_1 turns on.
The source current does not instantly equal the load current because of L_s. Consequently, the diode D_2 must remain on while the current in L_s and D_1 increases to the load.
During the interval when both the diodes are on is called the **commutation time** or **commutation interval**.

Definition

Commutation is a process of transferring the load current from once switch to another.

Here the line voltage makes the commutation happens and therefore it is called natural commutation

Effect of source inductance

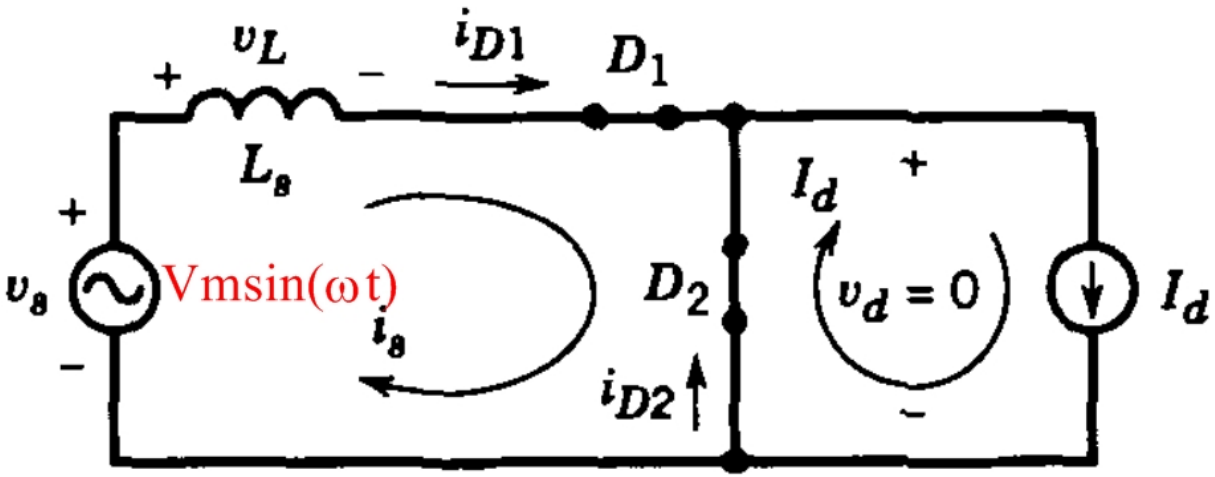
When D_1 and D_2 are on, the voltage across L_s is

$$v_{Ls} = V_m sin(\omega t) \tag{17}$$

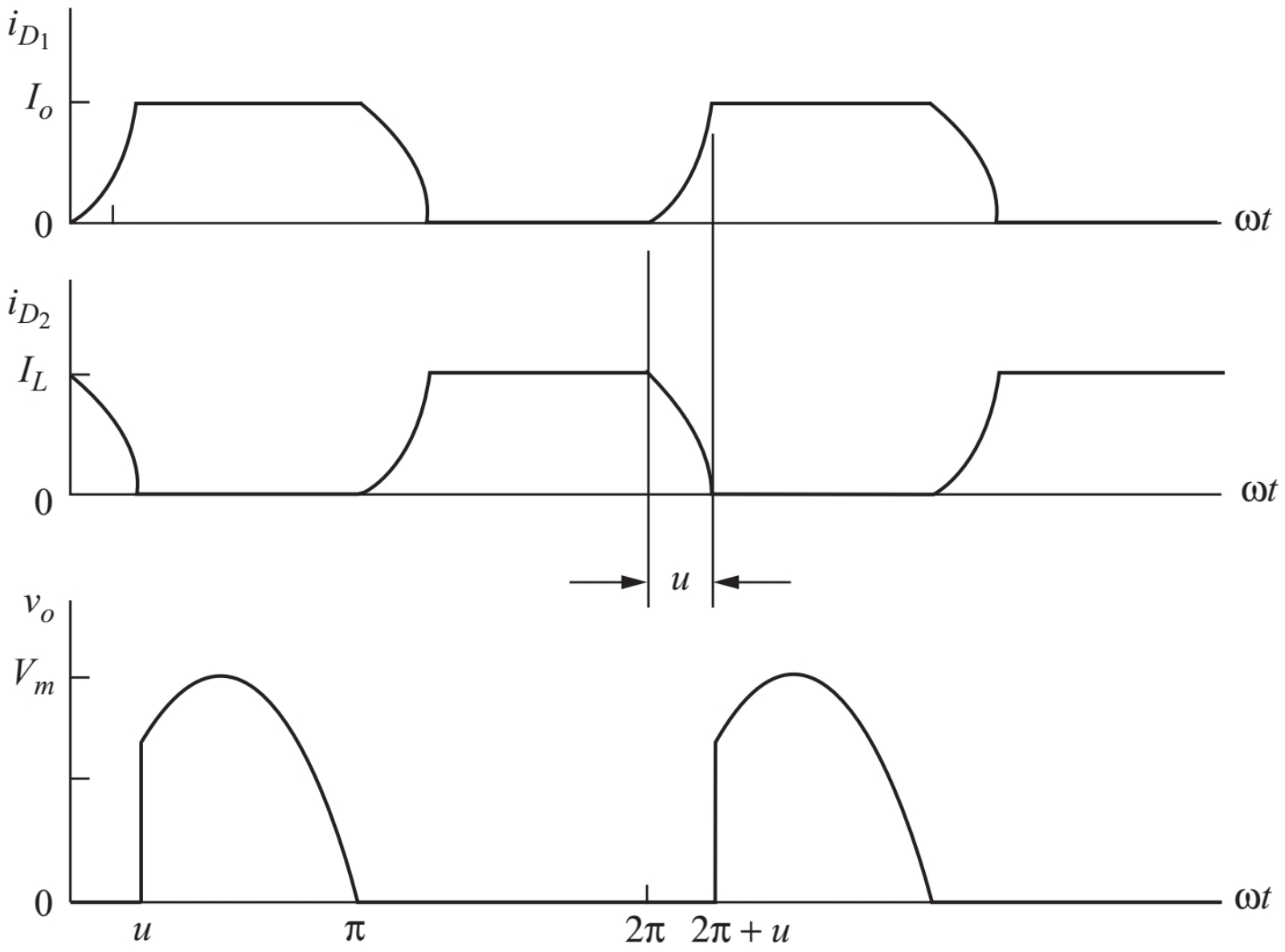
The current in the source inductance and hence in the source is

$$i_s = \frac{1}{\omega L_s}\int_0^{\omega t} v_{Ls} d(\omega t) + i_s(0) = \frac{1}{\omega L_s}\int_0^{\omega t} V_m sin(\omega t) d(\omega t) + 0 \tag{18}$$

$$i_s = \frac{V_m}{\omega L_s}(1 - cos\omega t) \tag{19}$$



Effect of source inductance

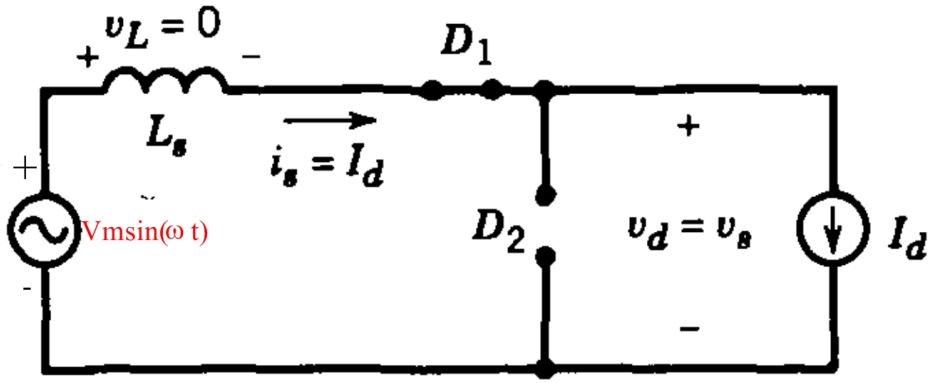


Effect of source inductance

Current in D_2 is calculated by using the KCL

$$i_{D,2} = I_L - i_s = I_L - \frac{V_m}{\omega L_s}(1 - cos\omega t) \tag{20}$$

The current in D_2 has an initial value I_L and it decreases to zero. The final form of the circuit is shown below.



Effect of source inductance

Let u be the angle at which the current reaches to zero at ωt, so

$$i_{D,2}(u) = I_L - i_s = I_L - \frac{V_m}{\omega L_s}(1 - cosu) = 0 \tag{21}$$

Solving for u,

$$u = cos^{-1}\left(1 - \frac{I_L \omega L_s}{V_m}\right) = cos^{-1}\left(1 - \frac{I_L X_s}{V_m}\right) \tag{22}$$

where, $X_s = \omega L_s$ is the reactance of the source.
On similar ground the commutation from D_1 to D_2 is analyzed similarly. The commutation angle affects the voltage across the load. Since the voltage across the load is zero when D_2 is conducting, the load voltage remains zero during commutation angle. The average output voltage with source inductance included is reduced as shown below

$$V_o = \frac{V_m}{2\pi}(1 + cosu) = \frac{V_m}{\pi}\underbrace{\left(1 - \frac{I_L X_s}{2V_m}\right)}_{\text{effect of } L_s} \tag{23}$$

Simulation — Effect of source inductance

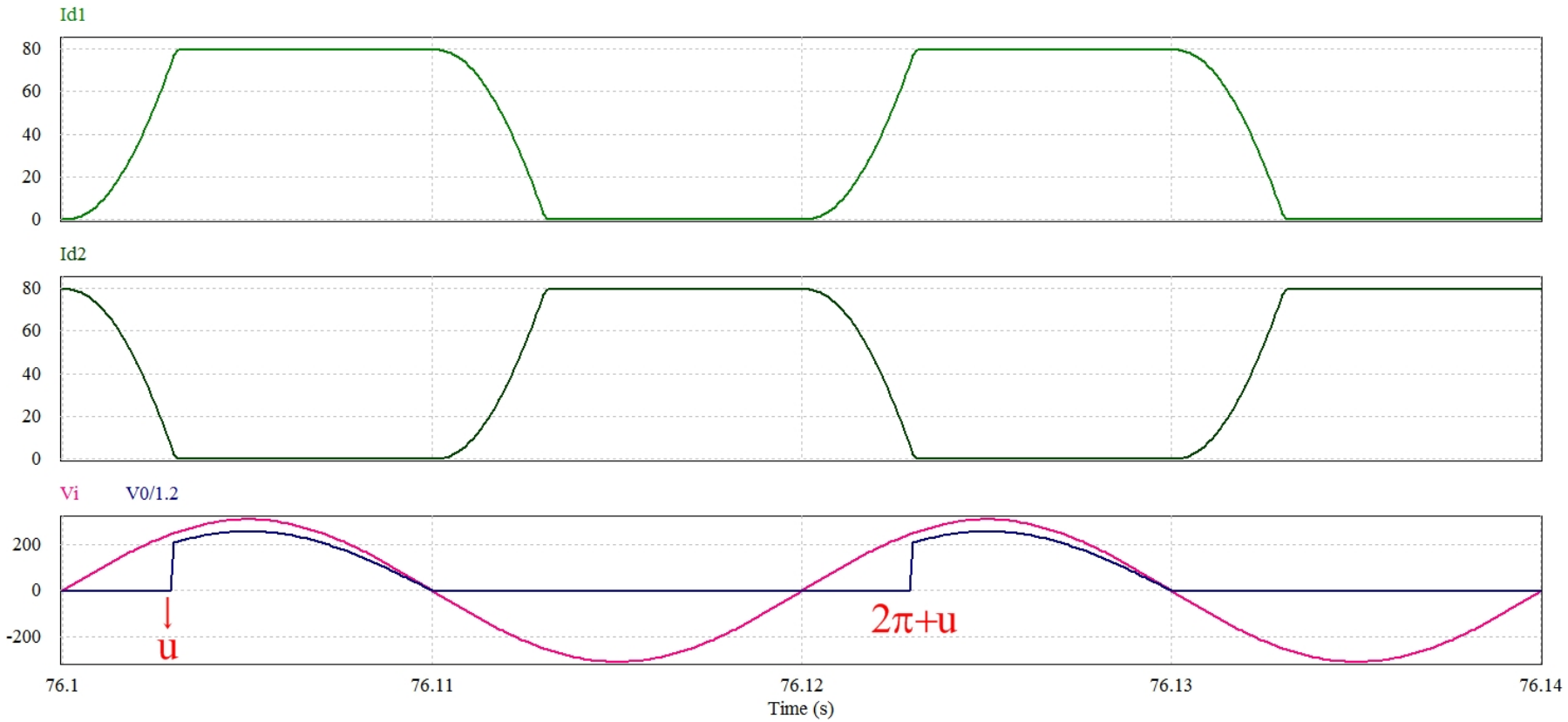


Figure: Ls=5m, L=50,R=1, Vs=312 at 50Hz